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Published in:
Optical Fiber Technology

Link to article, DOI:
[10.1016/j.yofte.2013.11.006](https://doi.org/10.1016/j.yofte.2013.11.006)

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

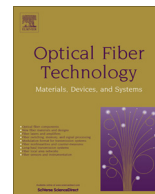
Citation (APA):
Borkowski, R., de Carvalho, L. H. H., Silva, E. P. D., Diniz, J. C. M., Zibar, D., de Oliveira, J. C. R. F., & Tafur Monroy, I. (2014). Experimental evaluation of prefiltering for 56 Gbaud DP-QPSK signal transmission in 75 GHz WDM grid. *Optical Fiber Technology*, 20(1), 39-43. <https://doi.org/10.1016/j.yofte.2013.11.006>

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Experimental evaluation of prefiltering for 56 Gbaud DP-QPSK signal transmission in 75 GHz WDM grid[☆]



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ARTICLE INFO

Article history:

Received 30 August 2013

Revised 17 November 2013

Available online 18 December 2013

Keywords:

Optical prefiltering

Optical modulation

Quaternary phase shift keying

Coherent detection

Optical transmission

Wavelength division multiplexing

ABSTRACT

We investigate optical prefiltering for 56 Gbaud (224 Gbit/s) electrical time-division multiplexed (ETDM) dual polarization (DP) quaternary phase shift keying (QPSK) transmission. Different transmitter-side optical filter shapes are tested and their bandwidths are varied. Comparison of studied filter shapes shows an advantage of a pre-emphasis filter. Subsequently, we perform a fiber transmission of the 56 Gbaud DP QPSK signal filtered with the 65 GHz pre-emphasis filter to fit the 75 GHz transmission grid. Bit error rate (BER) of the signal remains below forward error correction (FEC) limit after 300 km of fiber propagation.

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1. Introduction

One of the possible solutions to temporarily postpone fiber bandwidth exhaustion is to increase transmission symbol rates and spectral efficiency. Moving to dual polarization (DP) quaternary phase shift keyed (QPSK) transmissions at symbol rates of 56 Gbaud and beyond obtained by electrical time-division multiplexing (ETDM) is very demanding. This is due to a wideband nature of the transmitted signals, which set very high bandwidth (BW) requirements towards electrical components. Due to this, reported QPSK [1–3] or 16-QAM [4,5] transmission experiments at these high symbol rates are sparse. The wide optical spectrum of high symbol rate signals is also facing increased penalties due to cascaded filtering in fixed-grid reconfigurable optical add-drop multiplexers (ROADMs) [6].

With the advent of programmable optical filters, such as the WaveShaper (WS), controlled filtering at the transmitter (prefiltering) has recently been used to reduce bandwidth of signals with broad spectral support. While only a marginal performance penalty is introduced [7], it allows for transport in narrow grids resulting in increased spectral efficiency, as well as enhances signal tolerance

towards ROADMs filtering. Simultaneously, WS can be used to introduce pre-emphasis into the signal spectrum to combat BW limitation of electrical components as was recently reported for an 80 Gbaud system [3].

In this paper, we further investigate and compare different optical prefilters for 56 Gbaud DP-QPSK signal transmission. We analyze three different filter shapes (rectangular, Gaussian, pre-emphasis) and show that filtering can improve BER compared to unfiltered signal. We then analyze crosstalk from neighboring (interfering) channels and perform an experiment with five, 224 Gbit/s (DP QPSK and 16-QAM) 65 GHz-filtered channels aligned to 75 GHz grid, which leaves sufficient margin for propagation over at least 300 km of standard single-mode fiber (SSMF) with three ROADMs at 100 km spacing.

2. Experimental setup

Experimental setup is shown in Fig. 1. CW light at 1550.116 nm, being the channel under test (CUT), was originating from a 100 kHz-linewidth external cavity laser (ECL). The light source was followed by an optional pulse carver (PC). The PC was either clocked at 28 GHz which was resulting in a 67% duty cycle return-to-zero (67%RZ) pulse train or if no clock signal was present, the CW light was passing through without pulse carving, effectively removing PC from the setup. After the pulse carver, a 22 GHz BW in-phase/quadrature (I/Q) modulator was placed.

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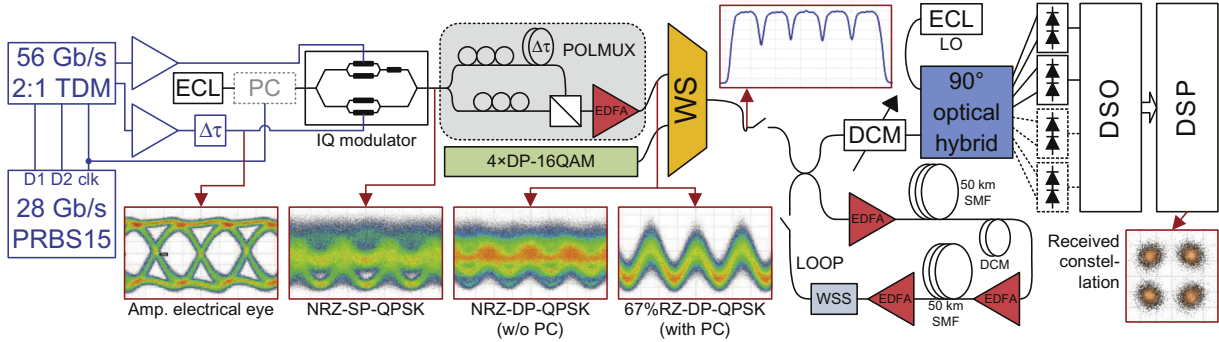


Fig. 1. Experimental setup, 56 Gbaud eye diagrams, optical spectrum (magnified in Fig. 3) and received constellation.

The electrical data signal, $2^{15} - 1$ pseudo-random binary sequence (PRBS-15), for the I/Q modulator originated from a 28 Gbit/s pattern generator with two outputs. Both electrical outputs produced sequences offset by a quarter of their length and were subsequently time-division multiplexed (TDM) to obtain 56 Gbit/s two-level electrical signal by interleaving both 28 Gbit/s input signals. Normal and inverted outputs of the TDM device were amplified, each to $4.4 V_{pp}$ (eye diagram shown in inset in Fig. 1), decorrelated by cables of different lengths and a delay line, and provided to I and Q inputs of the modulator to result in 112 Gbit/s (56 Gbaud) single polarization (SP) QPSK optical signal. This modulated signal was then polarization-division multiplexed by combining it with its delayed copy in the orthogonal polarization state. The obtained 224 Gbit/s (56 Gbaud) DP signal was subsequently amplified with erbium-doped fiber amplifier (EDFA) to account for components' losses and connected to one of the ports of the WS.

For experiments involving wavelength-division multiplexing (WDM), a subsystem generating four 28 Gbaud (224 Gbit/s) RZ-DP-16QAM interfering channels tightly surrounding the CUT was connected to another WS input. The WS was used to apply spectral shaping to connected input signals, separately to the CUT and the interfering channels, and combine them into one output signal.

For transmission experiments, signal was connected to a 2×50 km SSMF loop with a dispersion compensating module (DCM) between both spans, a wavelength-selective switch (WSS) to emulate ROADM filtering and to equalize power, and EDFAs to compensate spans and WSSs losses. A variable DCM was connected at the loop output to fine-tune chromatic dispersion (CD) of the signal after propagation in the loop. The need for such accurate chromatic dispersion compensation was due to limited capabilities of the receiver, which are described further. For back-to-back experiments, the transmission loop was omitted and signal from the WS was directly connected to the receiver.

The receiver was built from discrete components as none of the available commercial 100G integrated coherent receivers exhibited sufficient performance with the CUT. The received signal was mixed with a local oscillator, CW signal from a 100 kHz-linewidth ECL spectrally separated from the CUT laser by a couple of hundreds of MHz, in a 90° optical hybrid. Four of the hybrid outputs, responsible for one of the polarizations, were supplied to two balanced photoreceivers (BPRXs) with 30 GHz BW. Since BPRXs were equipped with limiting transimpedance amplifiers (TIAs), their output amplitude was effectively limited to two levels. This, in turn, prevented digital signal processing-based (DSP-based) CD compensation and necessitated the use of DCM. One of the CUT polarizations was always aligned to the state of polarization received from the hybrid to assure minimum polarization mixing. Electrical signals from BPRXs were sampled at 80 GSa/s

(≈ 1.43 Sa/symbol) with 30 GHz-BW oscilloscope. Traces were captured and subsequently processed with offline DSP [7] algorithms to equalize received constellation.

2.1. Optical prefiltering

Unfiltered signal spectra are shown for reference in Fig. 2(a). Due to RZ shaping, the spectral support of RZ signal is approximately twice that of NRZ signal. Amplitude responses of filters applied to the WS are shown in Fig. 2(b–d). Designed and measured 3 dB and 10 dB responses are listed in Table 1.

The pre-emphasis filter (Fig. 2(d)) is an inverse of the transmitted signal spectrum in the interval equal to the filter BW and zero elsewhere. Effectively, it attenuates low- and mid-frequency components and results in approximately rectangular optical spectrum. The filter attenuation, α_{pre} , expressed in linear scale, where 1 corresponds to complete attenuation and 0 to no attenuation, is given by Eq. 1 as

$$\alpha_{pre}(f) = \begin{cases} 1 - \frac{\min P(f)}{P(f)} & \text{for } -\frac{BW}{2} \leq f \leq \frac{BW}{2} \\ 1 & \text{otherwise} \end{cases}, \quad (1)$$

where f is the optical frequency relative to the WDM channel center, $P(f)$ is the discrete optical power spectrum measured at the transmitter output, and BW is the filter 3 dB bandwidth. This filter a zero-forcing equalizer applied at the transmitter that helps to mitigate intersymbol interference (ISI). The optical spectrum processed with a set of those filters is shown in Fig. 3(a).

We compare it with two, simpler to implement filters. Rectangular (Fig. 2(b)) filter, as defined by Eq. 2 has a flat amplitude response across its BW and a sharp cutoff outside of its BW. Its attenuation, α_{rect} , is specified as

$$\alpha_{rect}(f) = \begin{cases} 0 & \text{for } -\frac{BW}{2} \leq f \leq \frac{BW}{2} \\ 1 & \text{otherwise} \end{cases}. \quad (2)$$

The specification of Gaussian filter is given by Eq. 3 (Fig. 2(c)). Its shape follows a Gaussian function with full width at half maximum equal to the filter BW. Spectral components outside of the WDM grid slot are cut off.

$$\alpha_{Gauss}(f) = \begin{cases} 1 - \exp\left(-\frac{f^2}{2[BW/(2\sqrt{2\ln 2})]^2}\right) & \text{for } -37.5 \text{ GHz} \leq f \leq 37.5 \text{ GHz} \\ 1 & \text{otherwise} \end{cases}. \quad (3)$$

As measured from the spectrum of the rectangular filter, the WS has a 0.85 dB/GHz roll-off in the transition band and bandwidth setting resolution of approximately 1 GHz.

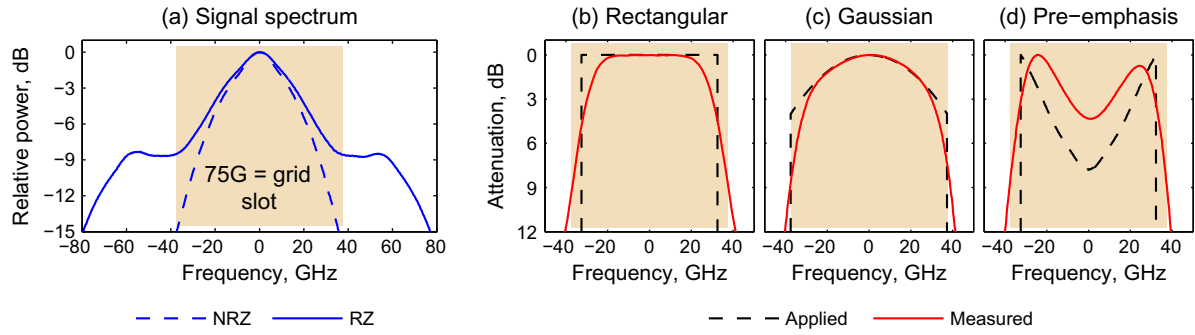


Fig. 2. (a) Comparison of 56 Gbaud DP-QPSK optical spectra for RZ and NRZ signals. (b–d) Applied and measured amplitude responses of implemented filters with 3 dB bandwidth of 65 GHz for transmission in 75 GHz grid (highlighted range).

Table 1

Designed (only filters) and measured 3 dB and 10 dB bandwidths for experimental signals and optical filters.

Signal/filter	Designed, GHz		Measured, GHz	
	3 dB	10 dB	3 dB	10 dB
RZ signal	–	–	32	128
NRZ signal	–	–	28	59
Rectangular	65	65	60	77
Gaussian	65	75	59	78
Pre-emphasis	65	65	64	77

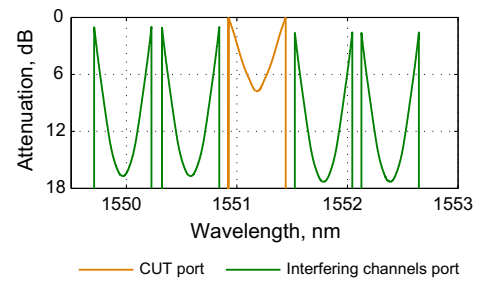


Fig. 4. Pre-emphasis filters applied to respective WS ports.

2.2. Optical prefiltering for WDM transmission

All channels in the WDM transmission experiment were equalized with a corresponding pre-emphasis filter. The back-to-back optical spectrum of the WDM system after filtering is shown in Fig. 3(a). The CUT was connected to one port of the WS, while interfering RZ-DP-16QAM channels were connected to another WS port. This was done to multiplex them together for transmission, and to prevent crosstalk to the CUT due to spectral overlap with interfering channels. Fig. 4 shows the filter applied to the interfering channels (green line), which is disjoint with the filter used for the CUT (yellow line). Possible strategies to introduce prefiltering into an actual system would be to use an optical equalizer as in [5] to either separately prefilter each channel at the output of each transmitter, or prefilter groups of odd and even channels, subsequently combining them for transmission in a narrow grid. Since both the CUT and interfering channels spectra were broader than 75 GHz slot of the transmission grid, the resulting spectral widths of signals after filtering with 65 GHz pre-emphasis filters were indistinguishable, as seen in Fig. 3(a).

3. Results

Back-to-back performance of the system as a function of optical signal-to-noise ratio (OSNR) is shown in Fig. 5(a). The system implementation penalty, as measured at BER of the forward error correction (FEC) limit of 3.8×10^{-3} , is 5 dB for both SP and DP signal. The horizontal separation between SP and DP curves is around 3 dB at FEC limit, indicating marginal penalty (theoretical minimum is 3 dB) due to polarization multiplexing. Only SP curve shows a small advantage of <1 dB for RZ shaping case. An error floor hits in around 1.5×10^{-4} and 3×10^{-4} for SP and DP cases respectively. Filter shapes under consideration are subsequently applied to the 67%RZ-shaped CUT while maintaining 23 dB OSNR. We start the investigation with a BW of 105 GHz for all filter shapes which is the minimum at which filter influence on the BER is negligible. As shown in Fig. 5(b), for rectangular and Gaussian filter shapes, the BER performance remains close to the reference for unfiltered RZ-DP signal, with the rectangular being slightly worse, until 65 GHz. For BWs lower than 65 GHz the BER starts to deteriorate, which for rectangular filter is very rapid due

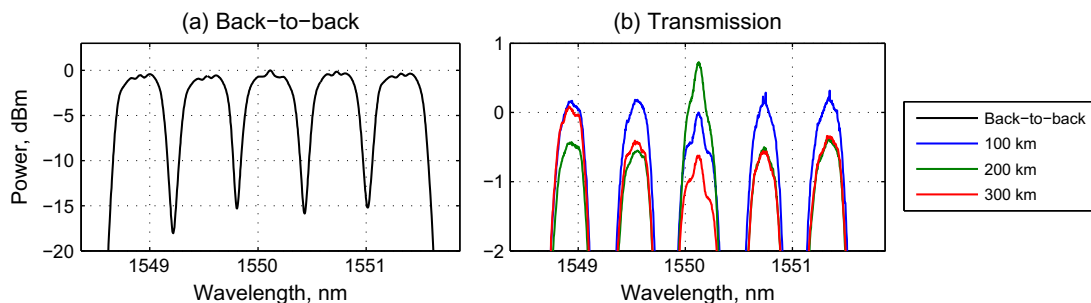


Fig. 3. (a) Back-to-back spectrum. (b) Evolution of transmission spectra after each loop circulation (power normalized w.r.t. the central QPSK channel at 100 km).

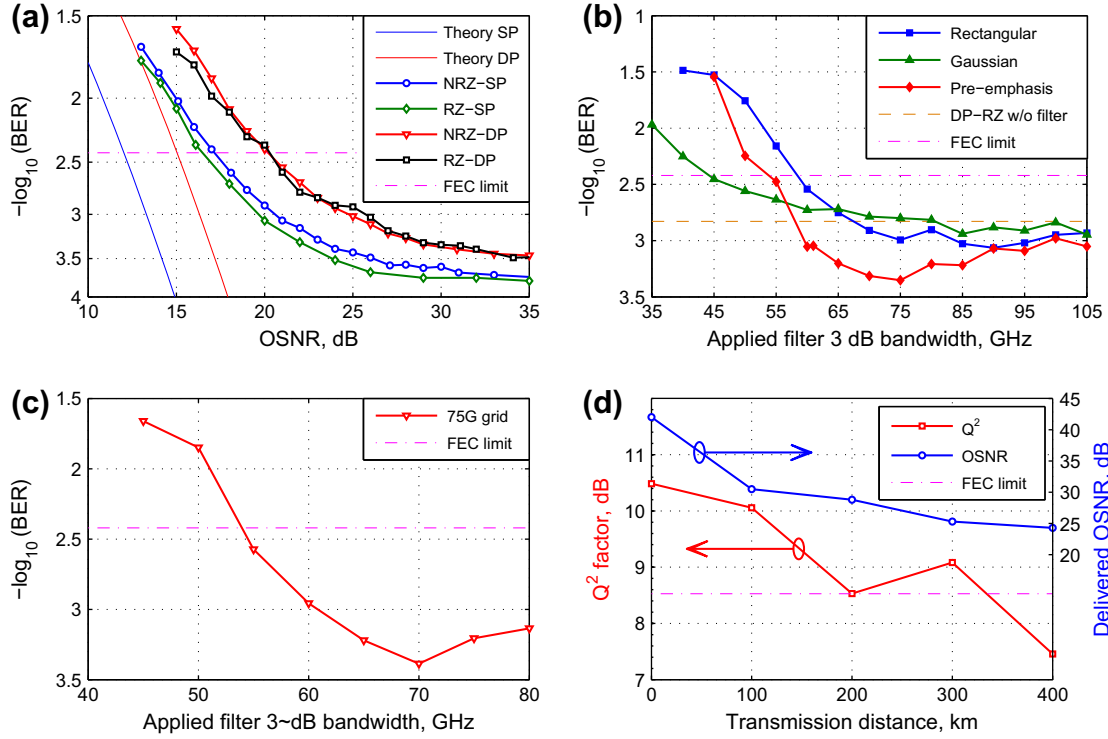


Fig. 5. (a) Back-to-back system performance. (b) Filtering performance of 56 Gbaud RZ-DP-QPSK signal at 23 dB OSNR. (c) Performance for varying bandwidth of pre-emphasis filter for transmission in 75 GHz grid at 23 dB OSNR. (d) BER performance and delivered OSNR of the CUT.

to strong ISI. For the pre-emphasis filter we can see an initial improvement in the BER from 3.0×10^{-3} at BW of 105 GHz down to a minimum of 4.4×10^{-4} at 75 GHz and again fast degradation below 60 GHz. This is explained by the fact that the pre-emphasis filter effectively works as amplification for high frequency components and counteracts the concatenated component frequency roll-off (which is steep as we are mostly using devices not designed to operate at 56 GHz). Thanks to transmitter-side pre-emphasis, noise amplification due to receiver-side equalization is less pronounced and in turn results in improved BER.

3.1. WDM transmission

We set up a WDM system with five channels in 75 GHz grid, as shown in Fig. 1, applied pre-emphasis filter to every channel, as described in Section 2.2, varied the filter BW and investigated crosstalk from interfering channels to the CUT. Results, shown in Fig. 5(c), indicate that the lowest crosstalk is obtained for a filter BW of 70 GHz. Considering cascaded ROADMs filtering, we decided to perform WDM transmission experiment with a filter BW of 65 GHz to increase margin for filter narrowing. The optical spectrum of the WDM signal, with each channel filtered with a corresponding pre-emphasis filter, is shown in Fig. 3(a). The evolution of this spectrum after each loop traversal, normalized to 0 dB for the CUT after 100 km, is presented in Fig. 3(b). The result of the WDM transmission experiment is shown in Fig. 5(d). We have managed to traverse 300 km (6×50 km) of SSMF with three WSSs in a compensated link while maintaining BER performance below the FEC limit.

4. Future work

Operating the system at high symbol rates is challenging and often requires a tradeoff between the bandwidth and linearity of

available electrical components. For instance, the coherent receiver used in the experimental setup was equipped with limiting TIAs. Because of this, accurate CD compensation was necessary at the end of the link to allow for successful signal digitization. We expect that a coherent receiver with linear TIAs, using adaptive CD compensation in DSP, will significantly improve the system performance. Moreover, even though both orthogonal polarization states were transmitted, only one of them could have been measured. For that reason an accurate polarization alignment of the signal entering the receiver was critical. Polarization state mismatch was negatively influencing BER, because crosstalk from non-received polarization could not have been mitigated in the follow-up DSP. We predict further BER improvement if data from both polarizations can be acquired and, subsequently, polarization demultiplexed with e.g. butterfly structure filter adapted by constant modulus algorithm (CMA) in digital domain. Despite those shortcomings, we still believe that our results are valid and provide an interesting input for further investigation of performance limits in optically-filtered 56 Gbaud systems. We also think that our work can provide guidelines when building or upgrading experimental setup to support high symbol rates.

5. Conclusions

We have compared different optical prefilters for 56 Gbaud DP-QPSK signal transmission. We found that for back-to-back case, an optical pre-emphasis filter (zero-forcing equalizer) with a bandwidth above 60 GHz resulted in BER improvement comparing to rectangular or Gaussian-shaped filters. We then demonstrated a 75 GHz-grid five-channel WDM transmission with channels shaped with 65 GHz 3 dB-bandwidth pre-emphasis filter, achieving 300 km transmission with BER performance below the FEC limit for the 56 Gbaud channel and passing through three WSSs.

Acknowledgment

We acknowledge Carolina Franciscangelis from CPqD for her help in performing experimental measurements.

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